Understanding the Physical Processes Underlying Solar Eruptions

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- Partnership between GSFC and U Michigan to understand the most important drivers of space weather

Approach:

- Develop MSEC (Modular Solar Eruptions Capability)
  - Second-generation NASA/LWS Strategic Capability designed for <u>exploratory</u> science by the general community
  - Designed for easy user modification and for local production runs (source code available)
- Build on heritage of SWMF
  - GB, *global background* module in which eruptions propagate
  - AR, high-res *active region* module in which eruptions originate
  - EE, *eruptive event* generator module
  - OB, *observables library* for generating SDO, STEREO, ACE, … measurements from simulations
  - TR, *training library* for new users

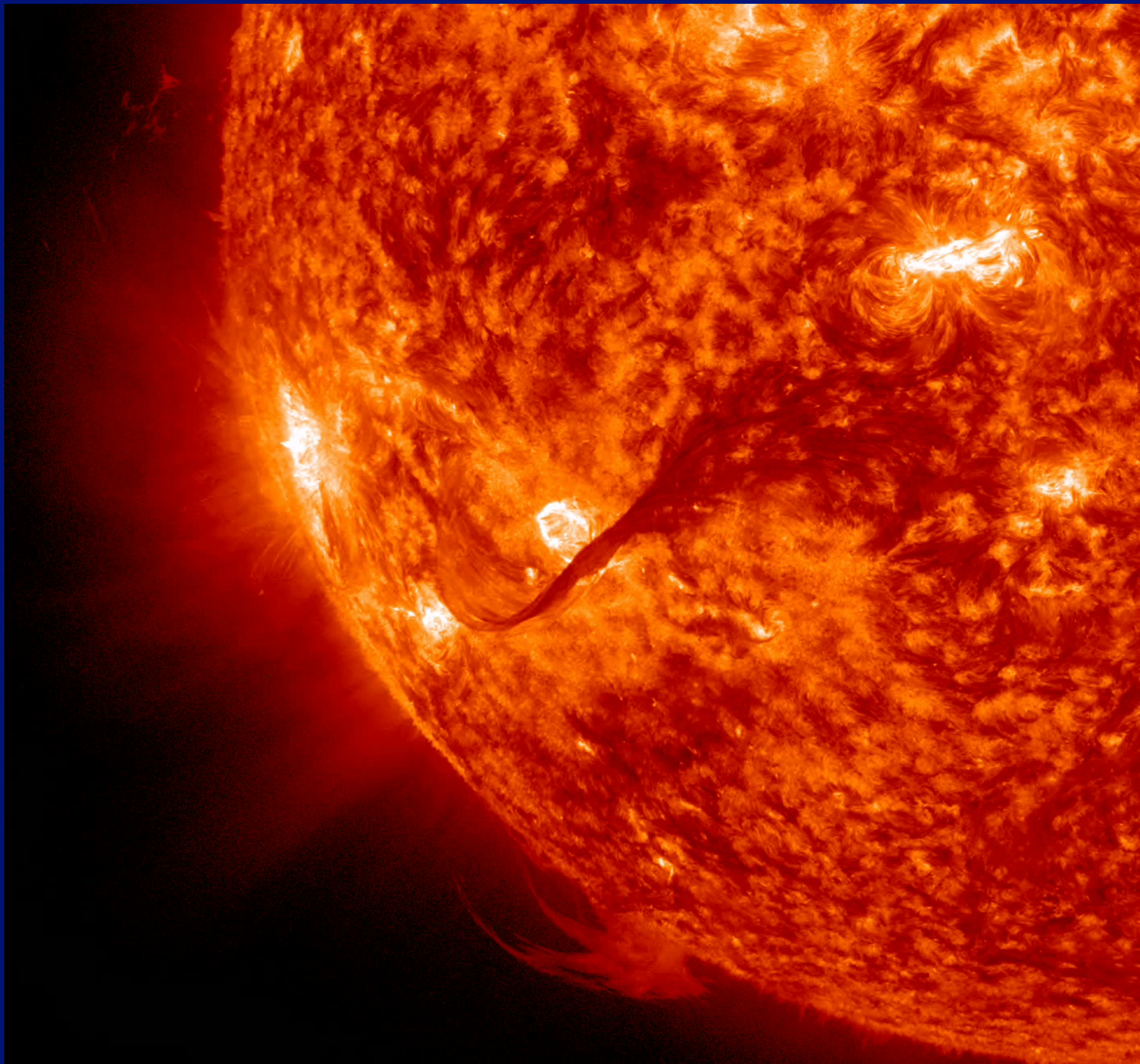
Understanding Solar Eruptions

Science Objective:

- Flares & CMEs, (primary drivers of space weather)

SDO observations of 08/31/12 eruptive flare:

- Pre-eruption structure *always* contains long sheared filament channel
- Balance between upward B pressure and downward tension
- System destabilizes, fast rise coincident with flare brightening
- Magnetic energy released into mass motions, heating, and energetic particles
- Filament and overlying corona ejected into solar wind



Understanding Solar Eruptions

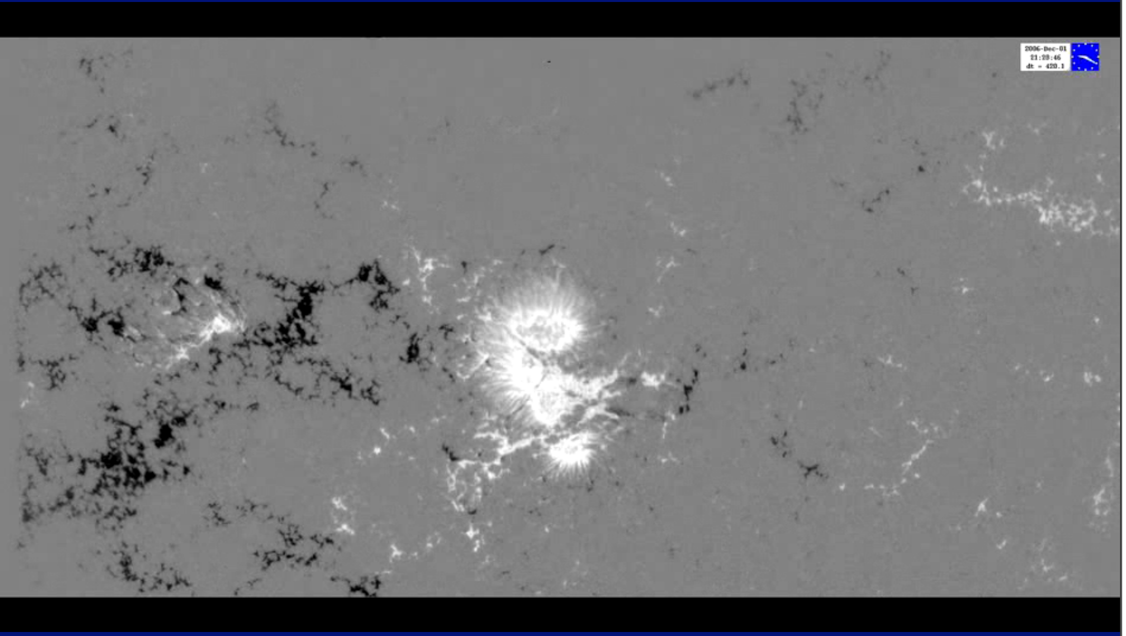
- How does the energy build up?
  - Why does magnetic shear concentrate at polarity inversion lines
  - Theories: **flux emergence**, flux cancellation, **helicity condensation**
- What destabilizes the system?
  - Ideal instability: kink or torus or loss of equilibrium
  - Resistive instability (reconnection): **breakout** or tether-cutting
- What causes the explosive energy release?
  - Ideal instability/loss of equilibrium or **fast flare reconnection**
- Where does the energy go?
  - Heating, mass acceleration, energetic particles, …
  - Need accurate models for **reconnection** (*Toth*)
- What are the space weather impacts?
  - Need most accurate possible models of **development** and **heliospheric propagation** (*van der Holst, Manchester*)

How does the energy build up?

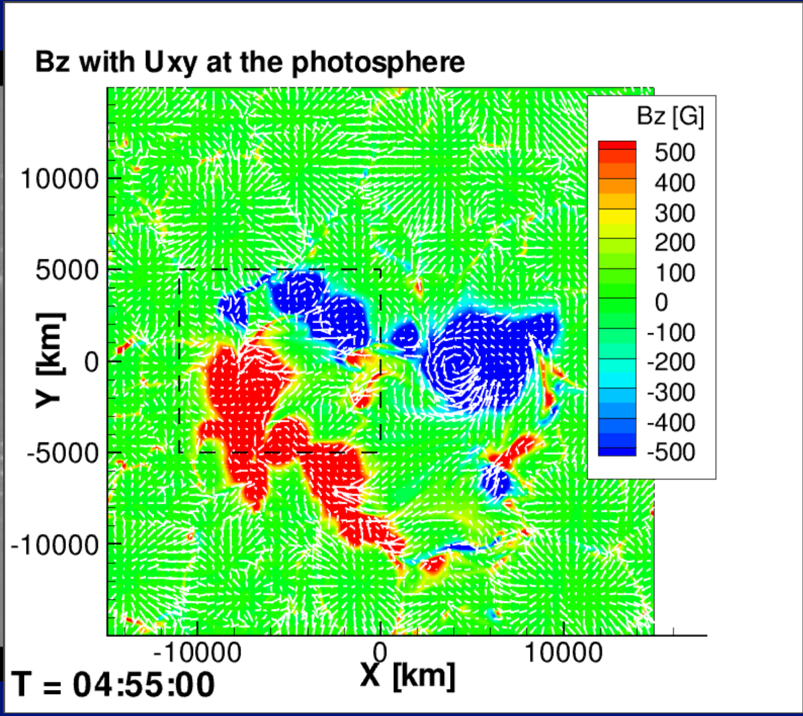
Flux Emergence:

- Often observe filament channel formation as part of emergence process (e.g., Okamoto et al 2009, Lites et al 2010)
- Emergence of subsurface twisted flux rope leads to sheared arcade at PIL (e.g., Manchester 2001, 2003, …; Fan 2001, Magara et al 2003, ..)
- Continued emergence/cancellation increases shear (Manchester et al 2004, Fang et al 2012)
- In principle, may lead to eruption, but need larger simulations

(Simulation from Fang et al 2013)



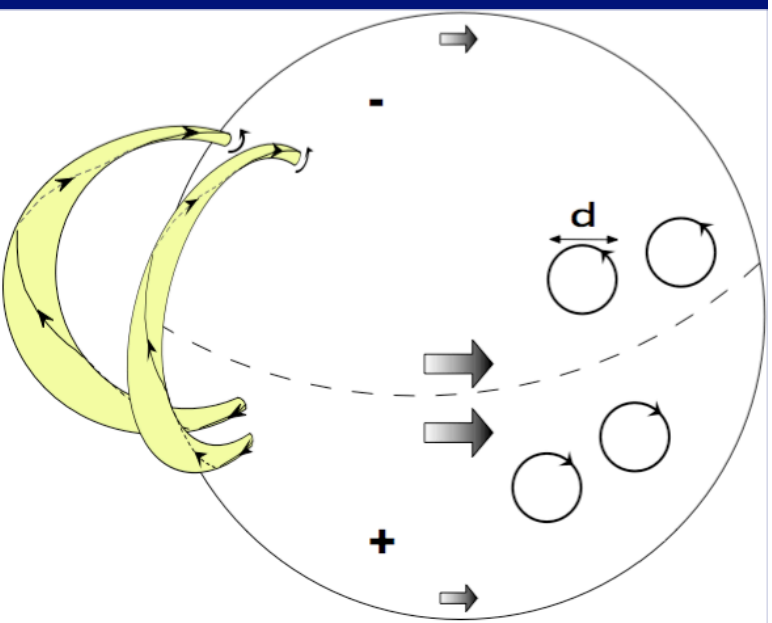
Hinode SOT observation 12/06

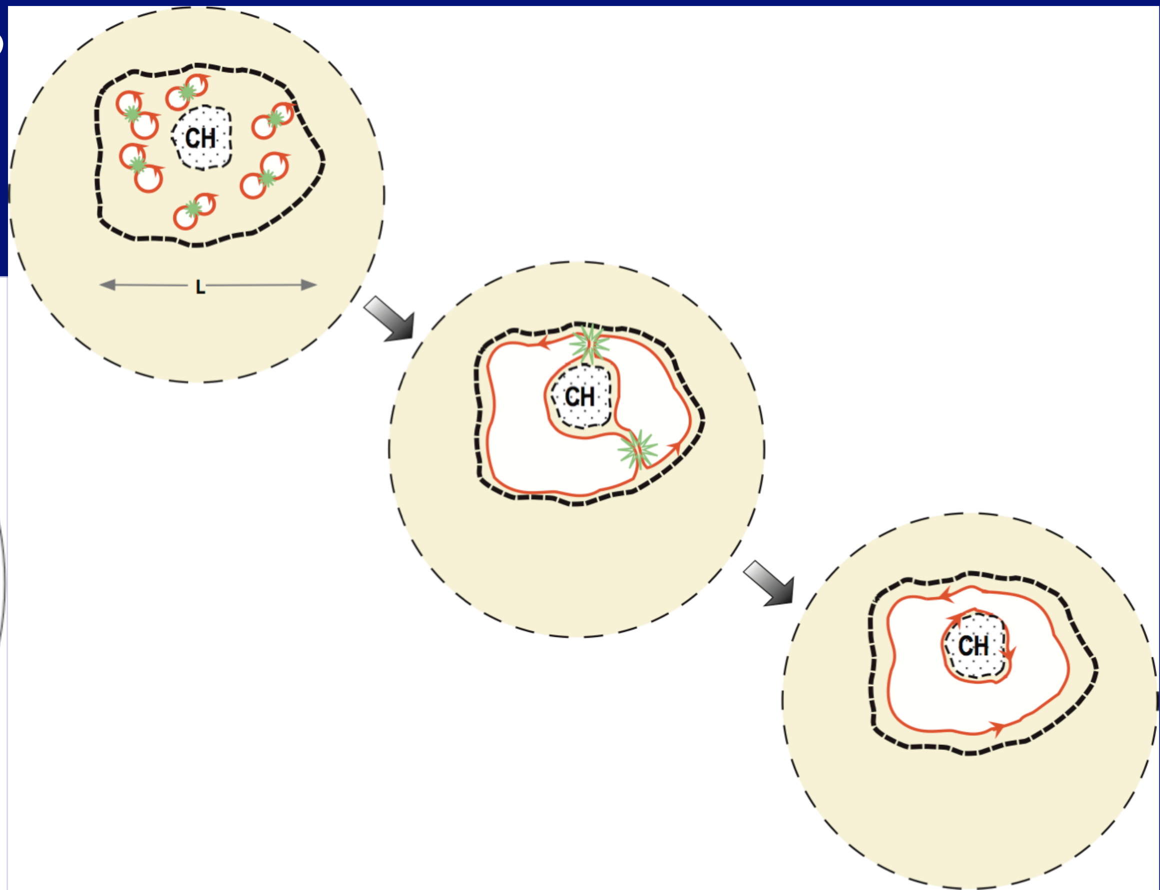


How does the energy build up?

Helicity Condensation: (Antiochos 2013)

- Helicity injected into closed corona must be conserved
- Net helicity injected due to hemispheric rule
- Closed loops with same sense of twist merge by reconnection
- Opposite sense “bounce” (Linton & Antiochos)
- Helicity (shear) condenses onto PIL and CH boundary
- Produces filament channel and slow wind





How does the energy build up?

- Rate of shear buildup at PIL given by:

  $v_L = v_p \ (d / L_1)$, where $L_1 = \sqrt{(L^2 - H^2)}$, *d is scale of motions,* v_p *is their speed, L is scale of PIL, and H scale of CH*

- Helicity spectrum:

  $\theta_\lambda \sim \lambda^{-2}$, except at largest scale *L* where shear builds up

- Physical origin of shear buildup at CH boundary:

  $H_T = \Phi_S \, \Phi_{L1} + \Phi_S \, \Phi_{CH}$

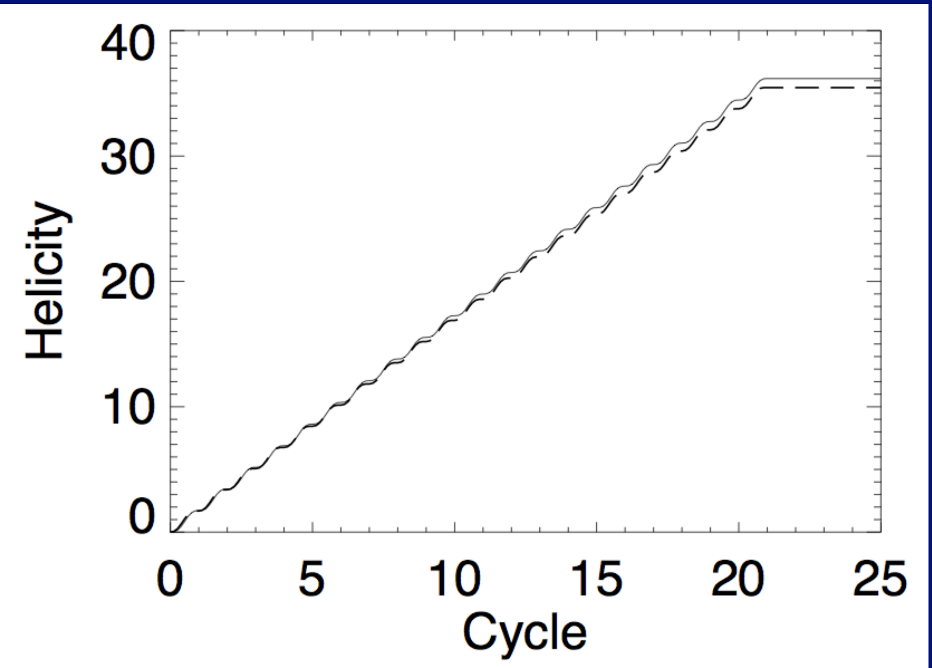
  But coronal hole cannot contribute to helicity; therefore, need canceling helicity:

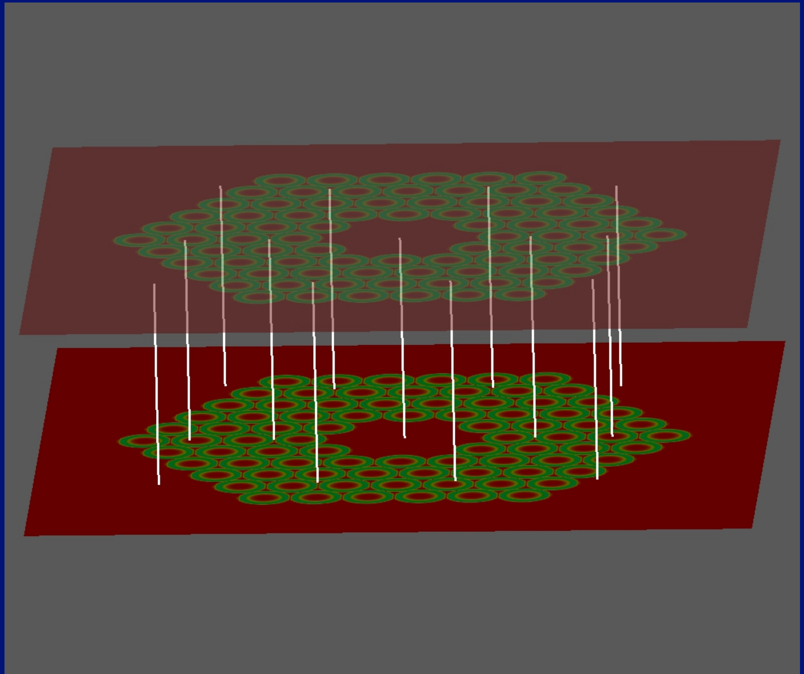
  $H_{CH} = - \Phi_S \, \Phi_{CH}$

Modeling Helicity-Condensation

(Zhao et al., Knizhnik et al)

- Start with usual uniform field between two photospheric plates, a la Parker
- Apply slow twists at plates ~ supergranular flows
- Specify various cases for number and extent of flows
- "PIL" and "CH" given by boundaries of flow region
- Use *ARMS* MHD code to calculate evolution
- Helicity conserved to excellent accuracy



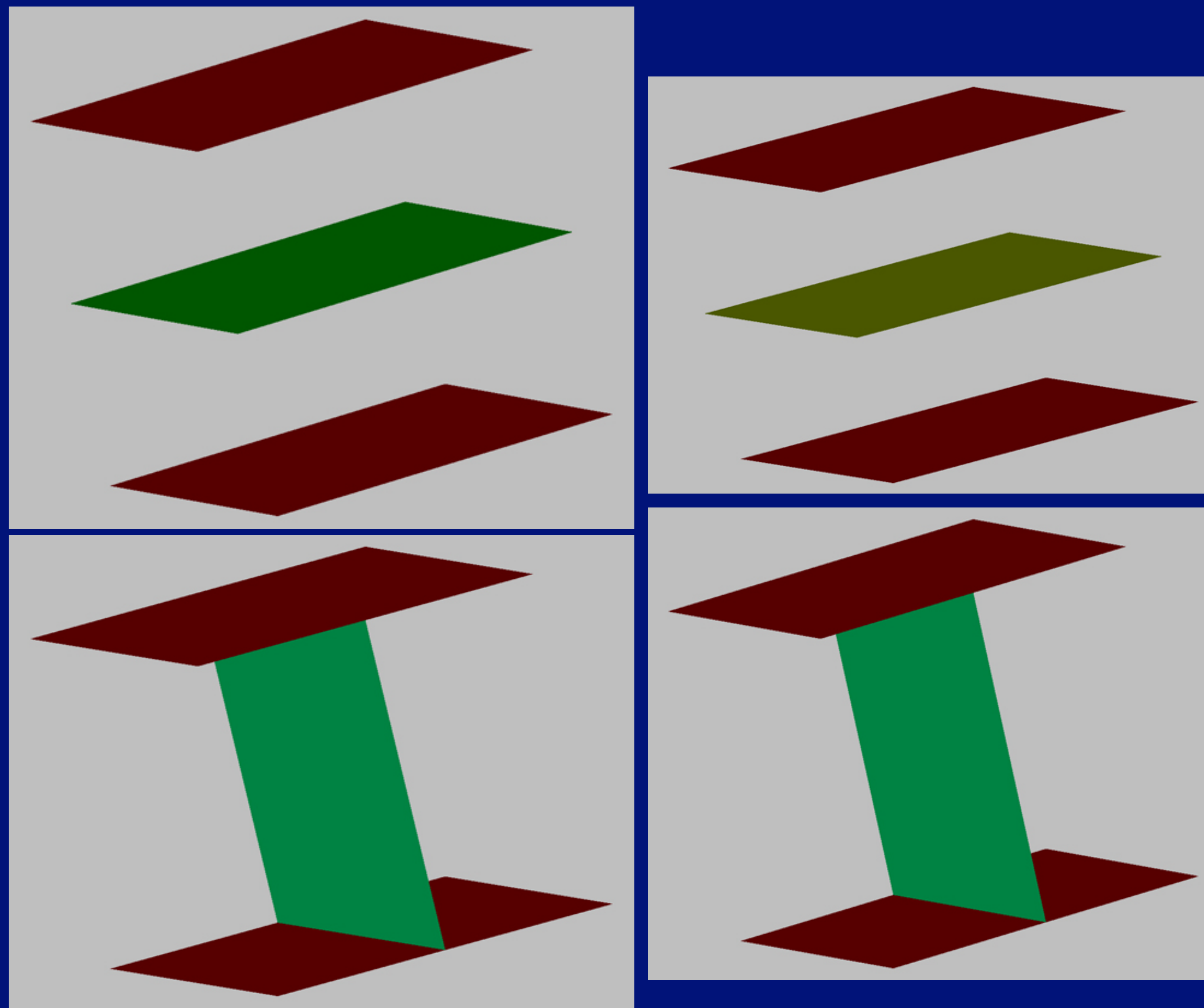


Modeling Helicity-Condensation

Interaction of two twisted coronal loops:

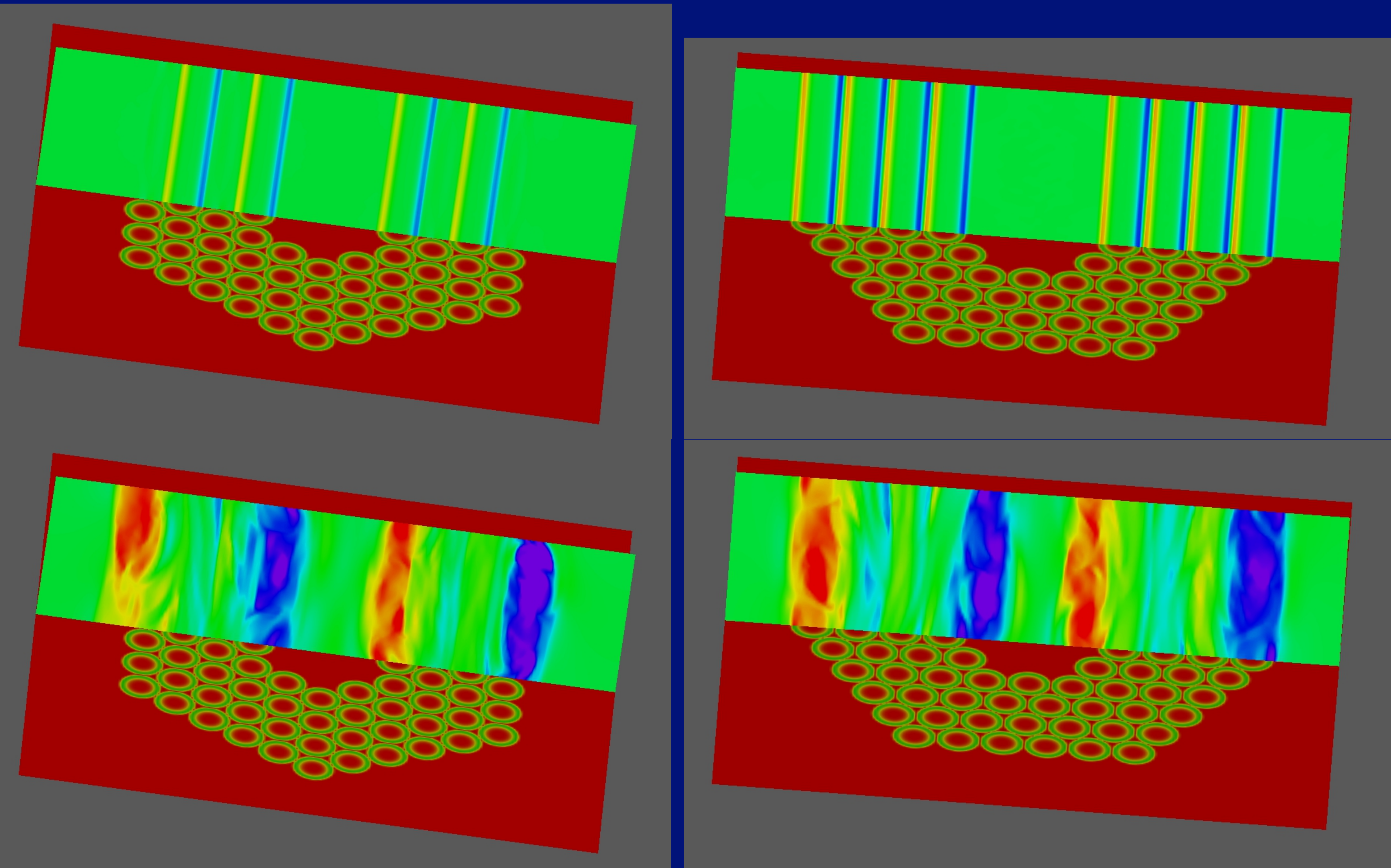
For same twist see reconnection and merger, opposite twist only kink

(from Zhao, DeVore and Antiochos, 2014)



Modeling Helicity-Condensation

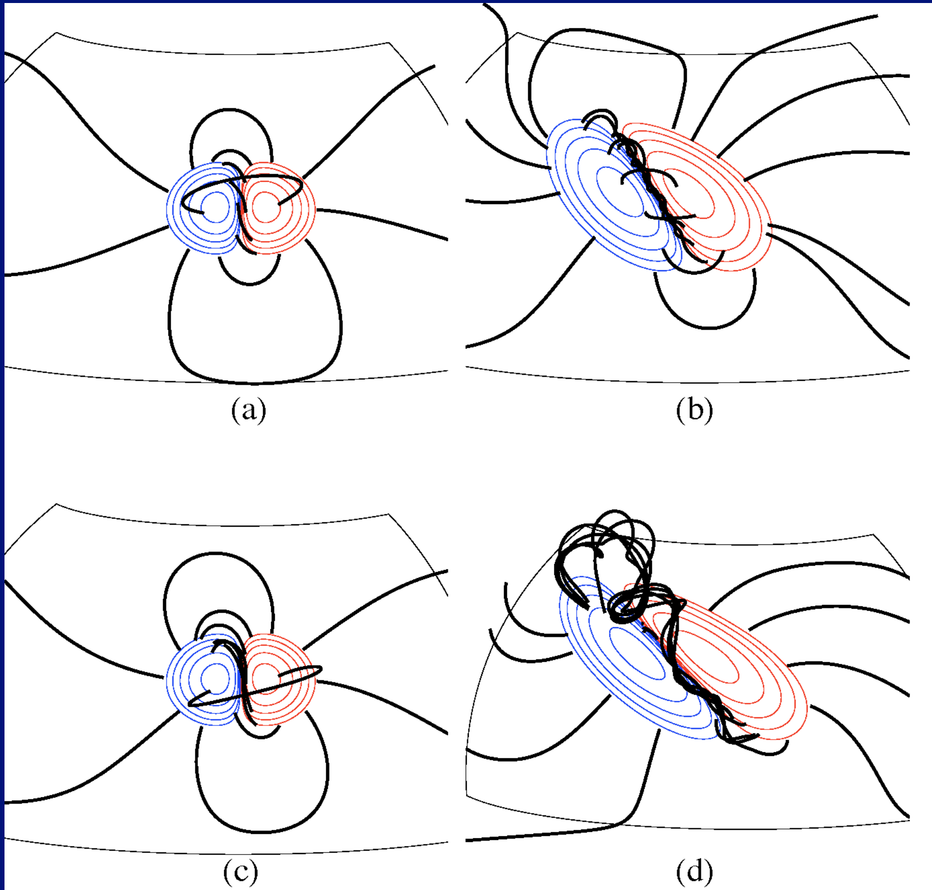
Interaction of 84 twisted coronal loops (Knizhnik, DeVore & Antiochos 2014)



Filament Channel Formation

(Mackay, DeVore, & Antiochos 2013)

- Magneto-frictional model for global field evolution
  - Includes diff. rotation, meridional flow, surface diffusion (Van Ballegooijen & Mackay)
- Wrong chirality for E-W PIL
- Added supergranular helicity injection and condensation to model
- Yields correct hemispheric rule for sufficiently large helicity condensation
- Also yields sheared filament channel rather than highly twisted flux rope

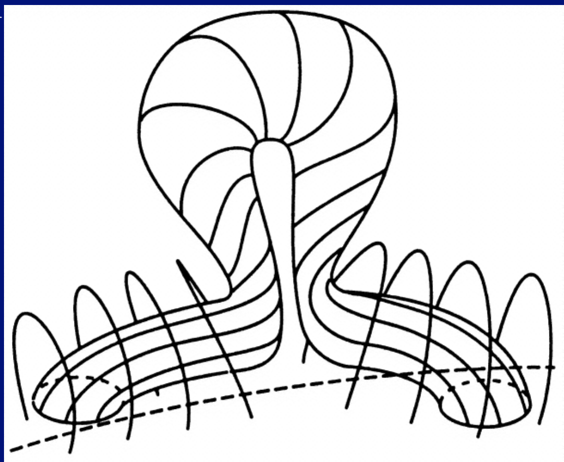


What destabilizes system?

Need explosive removal of overlying tension

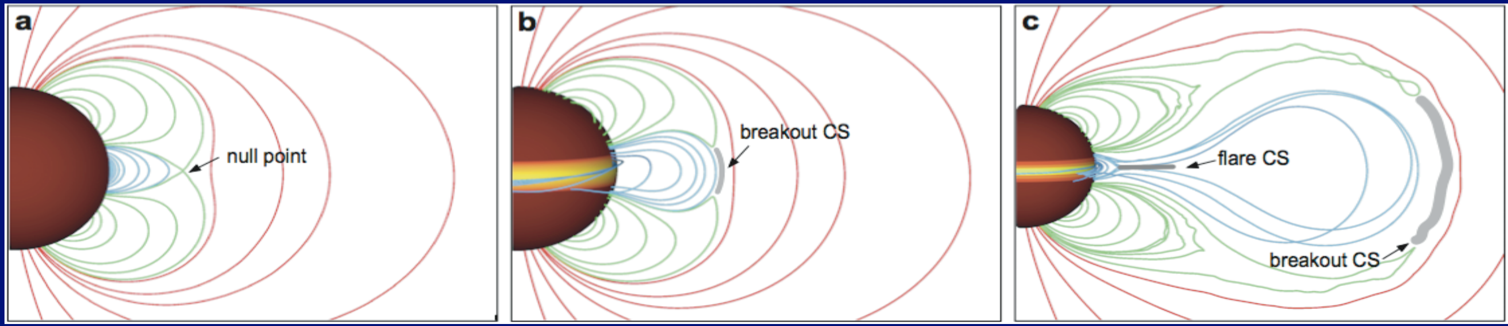
- Ideal instability/LOE: (e.g., Forbes et al, Low, van Ballegooijen et al, Sturrock, Mikic et al, Roussev et al, Fan et al, …)
  - Filament is topologically distinct, twisted flux rope prior to eruption

(Sturrock, 2002)



- Resistive: (e.g., Moore et al, Antiochos et al, Aulanier, MacNeice et al, Lynch, …)
  - Filament is topologically part of overlying system
  - Reconnection changes topology, removing overlying field

Karpen et al 2012



We (the community) will explore all mechanisms!

Build up and destabilization

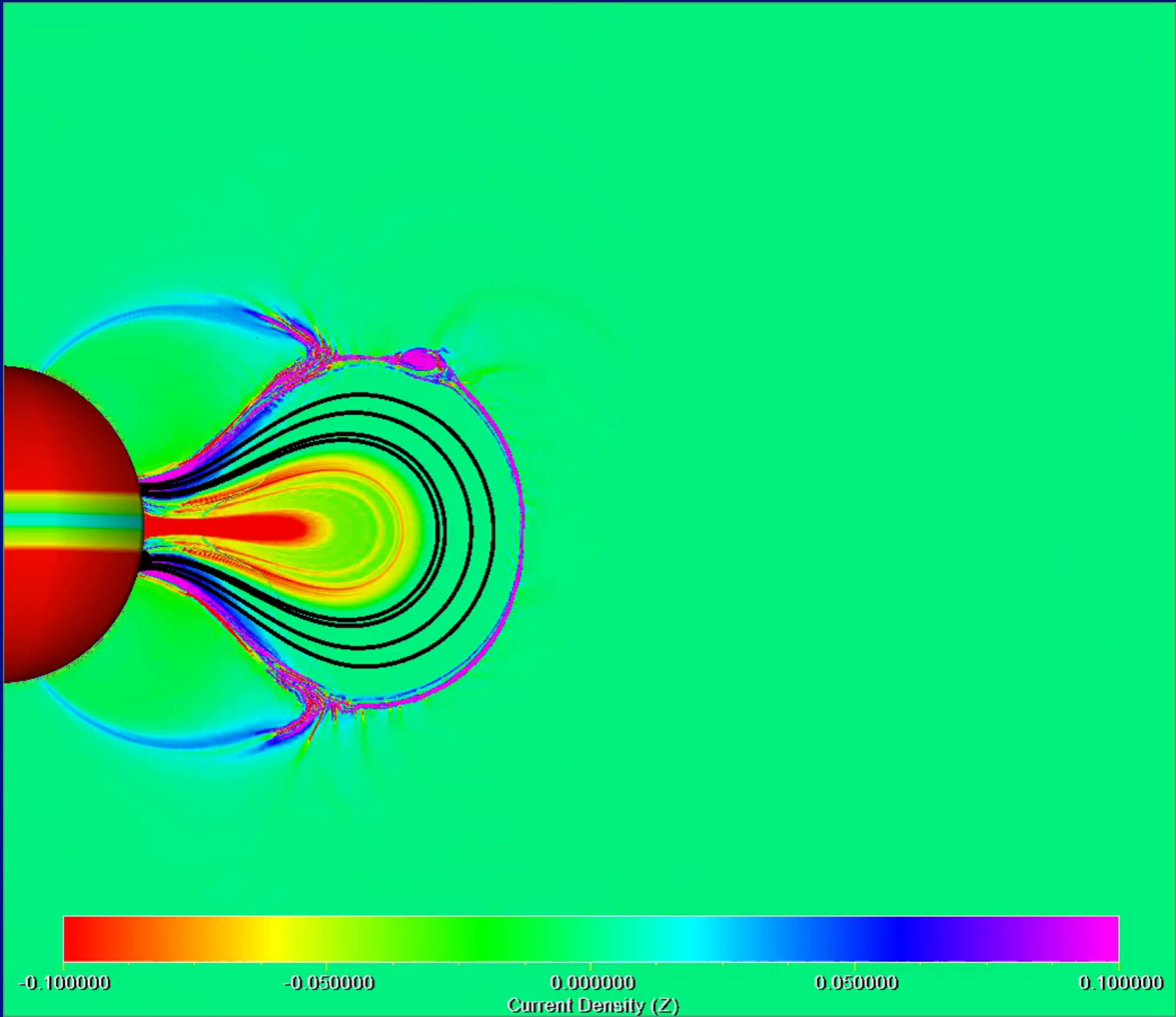
- Both flux emergence and helicity condensation can produce the free energy required for CME/flares
- Will model emergence for AR scale system and verify eruption
  - Determine whether ideal or reconnection-driven
  - Determine predictors for eruption
  - Test/validate with Hinode & SDO vector B observations
- Will model helicity condensation onto PILs and coronal holes
  - Determine whether results in MHD eruption
  - Test/validate with SDO vector B observations
  - Determine predictions for SPP & SO

What Causes Explosive Energy Release?

Fast Flare Reconnection

(Guidoni et al 2014)

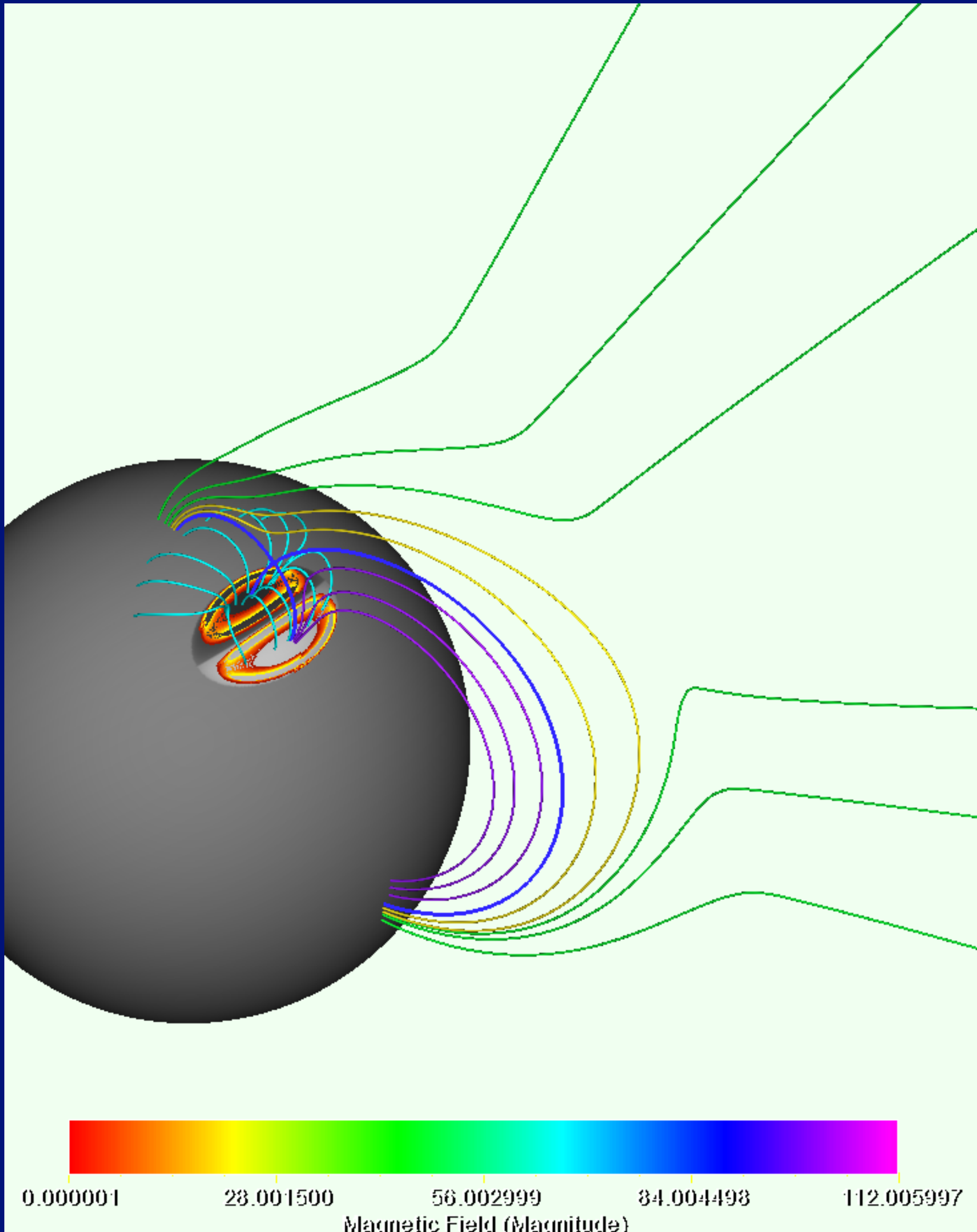
- Evolution slow and weakly energetic until flare reconnection onset
- Flare reconnection releases bulk of energy: CME acceleration, particle acceleration, heating, shock
- Dynamics dominated by island formation
- Kinetic processes critically important



What Causes Explosive Energy Release?

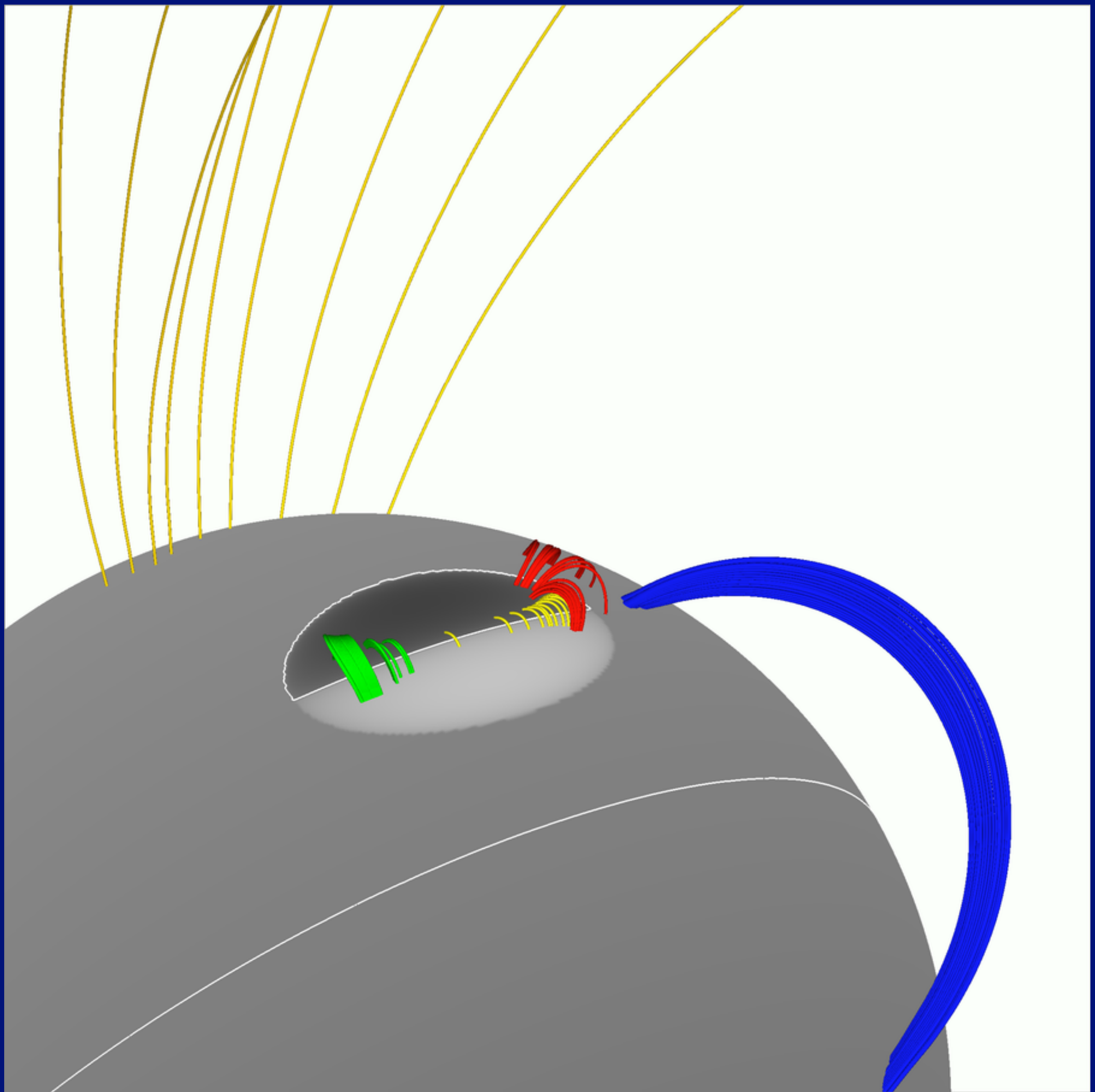
- Extension to fully 3D system
- Include solar wind
- Breakout reconnection has major implications for particle escape
- Explains impulsive SEP

(Masson et al 2014)



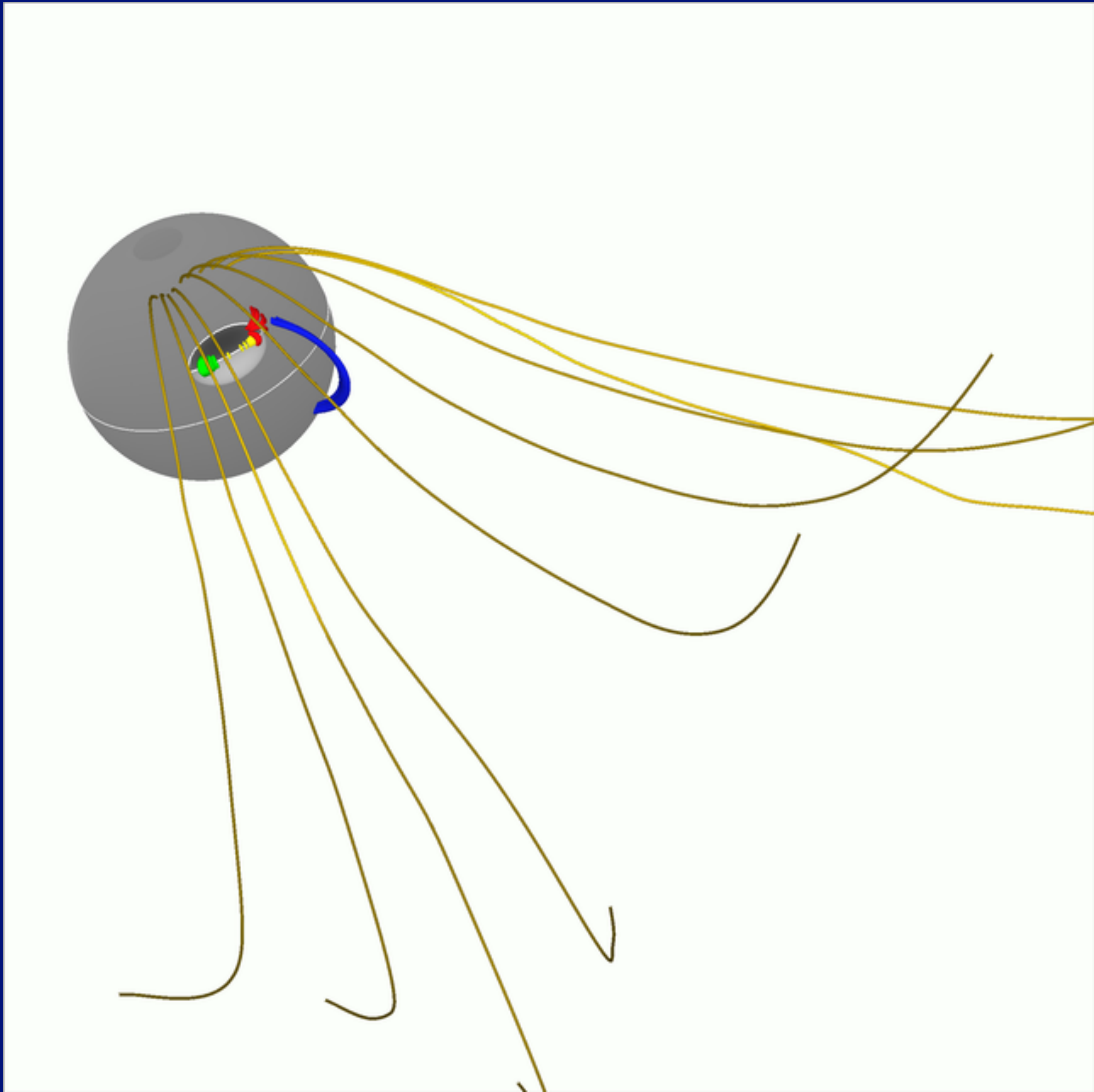
What Causes Explosive Energy Release?

- In 3D have multiple reconnections with neighboring flux systems
- Produces coronal dimmings
- "End" effects due to finite length for eruption

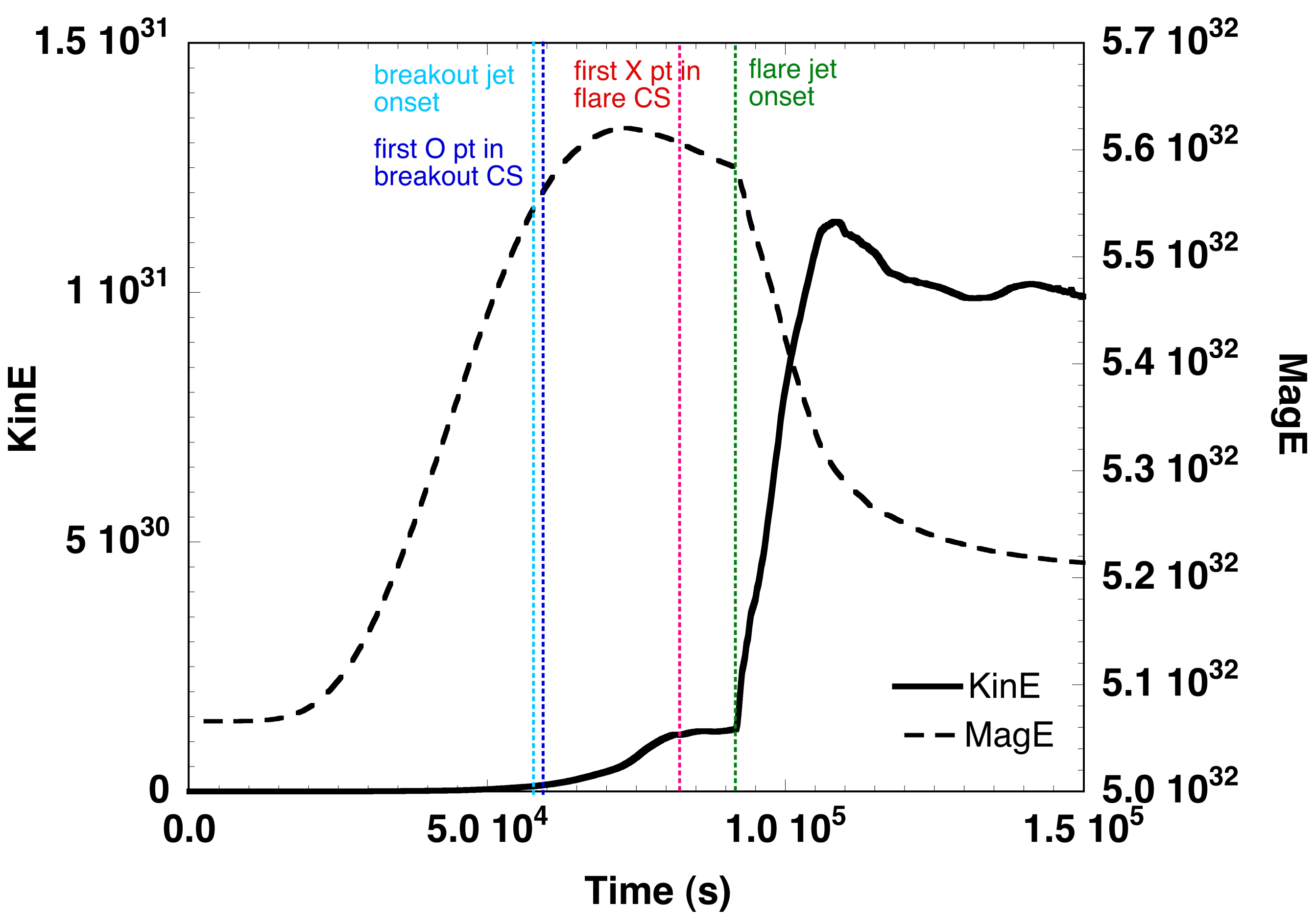


What Causes Explosive Energy Release?

- Reconnection between erupting flux rope and neighboring open flux
- Allows flare particles to escape
- For SEP prediction, need accurate models for global coronal topology

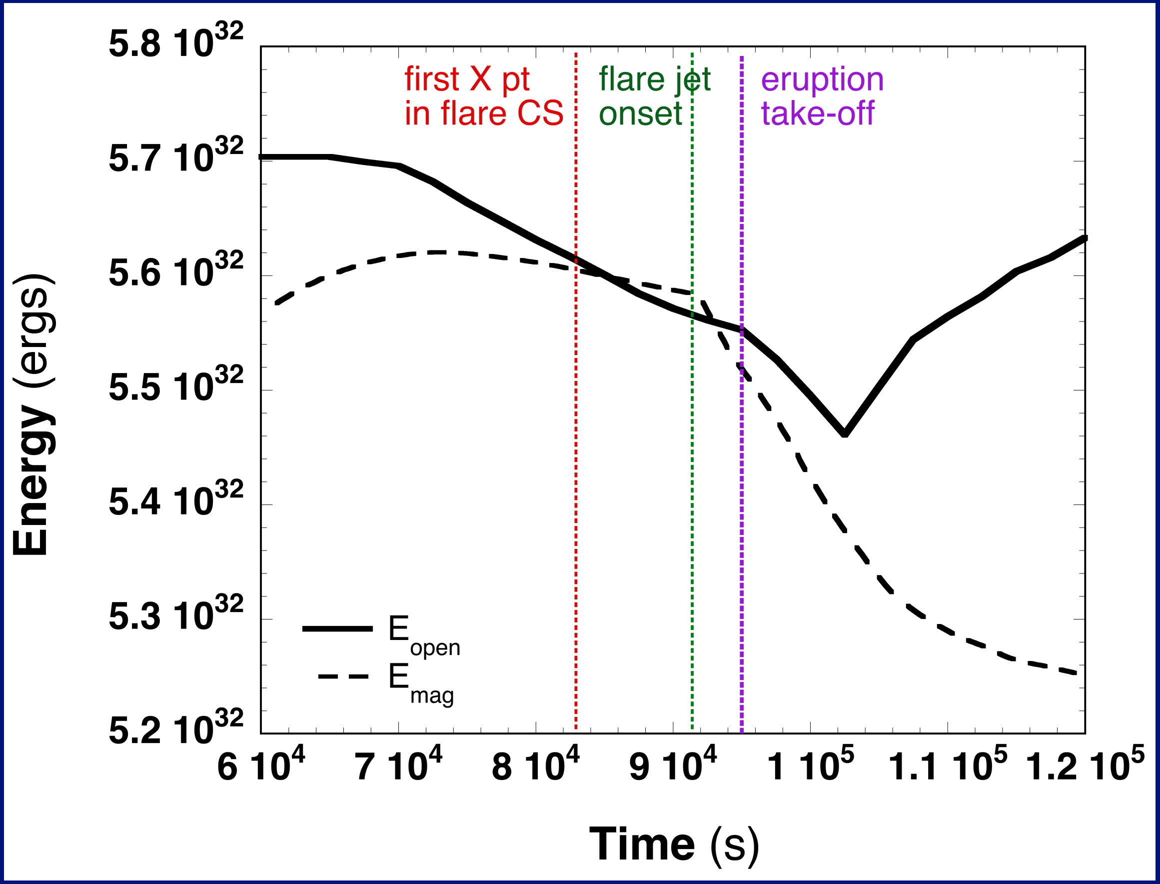


Energy Evolution



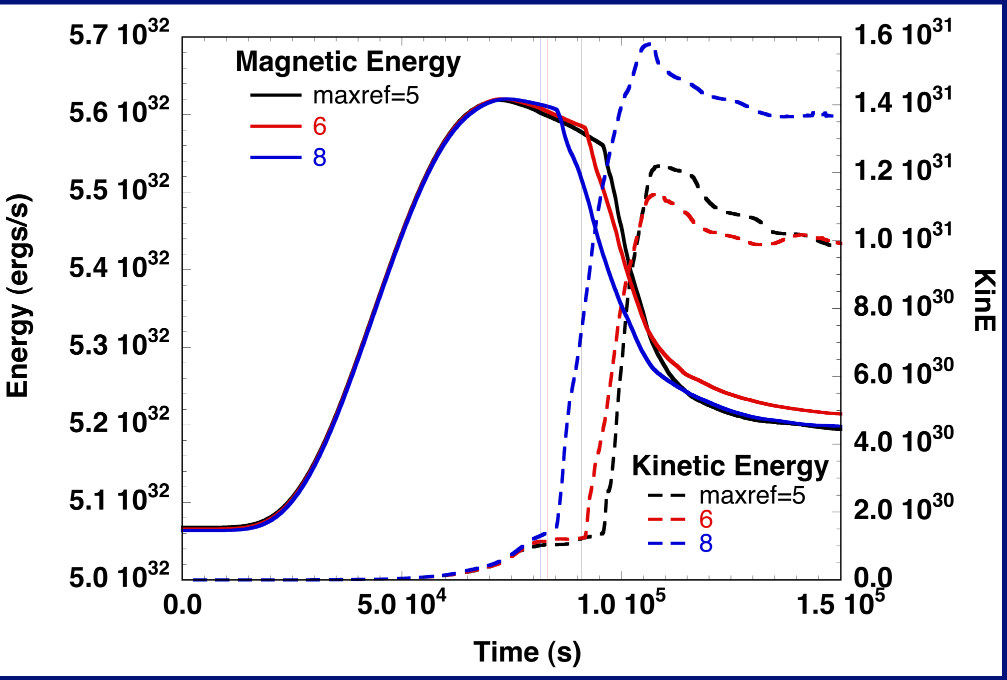
- Time history of magnetic and kinetic energies
  - CME onset corresponds to start of breakout reconnection
  - “Take-off” corresponds to start of fast flare reconnection
- Explosiveness all due to flare reconnection

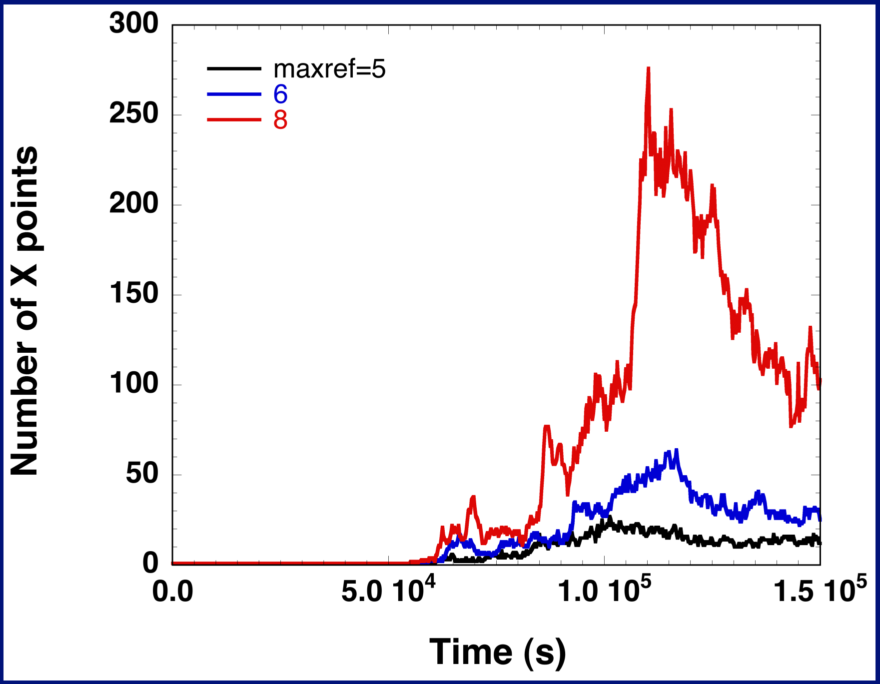
Eruption Mechanism



- Magnetic energy vs energy of corresponding “open” state
  - No evidence for ideal instability/loss of equilibrium
  - Resistive instability

Where does the energy go?





- Basic onset and explosive evolution unchanged with S
- Eruption dominated by MHD, E partitioning by kinetics
- Number of islands scales ~ S
- For large S may dominate particle acceleration, as in Drake et al.

Energy release and partitioning

- Flare reconnection the central process of major solar eruptions
  - Little evidence for ideal processes in any of our work
  - Emphasizes key role of reconnection – similar to magnetosphere
- Need to validate/refute with observations
- Energy partitioning determined by reconnection dynamics
  - Will incorporate multiscale coupling into models
  - Anticipate major advances in both basic understanding and space weather modeling